

## Consistent Tropical Cyclone Wind and Wave Forecasts for the U.S. Navy

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### ABSTRACT

A new algorithm to generate wave heights consistent with tropical cyclone official forecasts from the Joint Typhoon Warning Center (JTWC) has been developed. The process involves generating synthetic observations from the forecast track and the 34-, 50-, and 64-kt wind radii. The JTWC estimate of the radius of maximum winds is used in the algorithm to generate observations for the forecast intensity (wind), and the JTWC-estimated radius of the outermost closed isobar is used to assign observations at the outermost extent of the tropical cyclone circulation. These observations are then interpolated to a high-resolution latitude–longitude grid covering the entire extent of the circulation. Finally, numerical weather prediction (NWP) model fields are obtained for each forecast time, the NWP model forecast tropical cyclone is removed from these fields, and the new JTWC vortex is inserted without blending zones between the vortex and the background. These modified fields are then used as input into a wave model to generate waves consistent with the JTWC forecasts. The algorithm is applied to Typhoon Yagi (2006), in anticipation of which U.S. Navy ships were moved from Tokyo Bay to an area off the southeastern coast of Kyushu. The decision to move (sortie) the ships was based on NWP model-driven long-range wave forecasts that indicated high seas impacting the coast in the vicinity of Tokyo Bay. The sortie decision was made approximately 84 h in advance of the high seas in order to give ships time to steam the approximately 500 n mi to safety. Results from the new algorithm indicate that the high seas would not affect the coast near Tokyo Bay within 84 h. This specific forecast verifies, but altimeter observations show that it does not outperform, the NWP model-driven wave analysis and forecasts for this particular case. Overall, the performance of the new algorithm is dependent on the JTWC tropical cyclone forecast performance, which has generally outperformed those of the NWP model over the last several years.

### 1. Introduction

Typhoon-generated waves have long been a major concern for U.S. Navy vessels and installations. The worst naval disaster in U.S. history was the result of Typhoon Cobra on 18 December 1944 (Drury and Clavin 2007). Typhoon Cobra was a small typhoon east of the Philippines with winds as high as 125 kt ( $1 \text{ kt} = 0.514 \text{ m s}^{-1}$ ) that generated 100-ft ( $1 \text{ ft} = 0.3048 \text{ m}$ ) waves in the path of Admiral Bull Halsey's fleet as it steamed toward

the Philippines to support General Douglas MacArthur's invasion of Luzon. Three ships broke up and sank with their crews (a total of 790 sailors). The decision to establish a typhoon warning center in the Pacific, which eventually became the Joint Typhoon Warning Center (JTWC), occurred in the aftermath of Typhoon Cobra. Incidents in the subsequent years continue to remind the U.S. Navy of the importance of accurate wind and wave forecasts during tropical cyclone events. Although the cost of a fleet sortie (where ships at a base are sailed out to sea and away from tropical cyclones) is expensive, the consequences of remaining in port could be far more devastating. Costs for a sortie from Yokosuka, Japan, could cost more than \$10 million (U.S. dollars), but the

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replacement cost of one aircraft carrier is approximately \$8.1 billion (U.S. Navy 2008b). To complicate matters, the sortie decisions are frequently made at least 72 h ahead of a tropical cyclone event to provide enough lead time for ships to get under way and out of the path of the approaching system. As a result, the navy periodically sorties ships from bases when, in retrospect, the sortie was not required. This was the case for the U.S. Navy ships stationed at Yokosuka during Typhoon Yagi (2006).

By 1200 UTC 19 September, Yagi (2006) was a 100-kt typhoon with estimated 34-kt wind radii of 115, 115, 110, and 90 nautical miles (1 n mi = 1.852 km) in the northeast, southeast, southwest, and northwest quadrants of the storm, respectively. The Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond 1991) run at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) is used to produce wind forcing for a third-generation spectral ocean wave model (WAVEWATCH III; Tolman 1991; Tolman et al. 2002), as described in Rogers et al. (2005). The NOGAPS tropical cyclone forecast for this time is shown in Fig. 1a. The initial NOGAPS position is within  $0.1^\circ$  latitude of the JTWC-analyzed position at the time, but the NOGAPS initial intensity (maximum wind speed) is only 46 kt. The NOGAPS initial 34-kt wind radii are 68, 179, 116, and 193 n mi in the northeast, southeast, southwest, and northwest quadrants, respectively, and are 69%, 55%, 5%, and 114% larger, respectively, than those analyzed by JTWC. To summarize, the NOGAPS initial intensity is approximately half the JTWC-analyzed intensity, and the average of the initial NOGAPS 34-kt wind radii is approximately 30% larger than the JTWC-analyzed 34-kt wind radii. The NOGAPS forecast track for 1200 UTC 19 September follows approximately the same path as the JTWC forecast track, but it approaches the Japanese coast earlier in the forecast. For example, the 72-h NOGAPS forecast position valid 1200 UTC 22 September is approximately 200 n mi closer to Japan than the JTWC forecast position valid at the same time. The 72-h NOGAPS forecast intensity (56 kt) is much lower than the JTWC forecast intensity (105 kt), and the NOGAPS 34-kt wind radii (229, 220, 103, and 169 n mi in the northeast, southeast, southwest, and northwest quadrants of the storm, respectively) are much larger than those in the JTWC 72-h forecast (140, 135, 135, and 135 n mi, respectively). With an implementation of WAVEWATCH III such as the one run at FNMOC (Rogers et al. 2005), these differences in tropical cyclone structure and motion could lead to inconsistencies between the operational JTWC tropical cyclone forecast and in the distribution of the significant wave heights. It has also been shown that inserting winds from a higher-resolution model such as the Geophysical Fluid Dynamics

Laboratory model (GFDL; Kurihara et al. 1998) into a global model [Global Forecast System (GFS); Moorthi et al. 2001] can provide improved prediction of the extreme sea states generated by hurricanes [North Atlantic Hurricane product (NAH); Tolman et al. 2005; Chao et al. 2005], so a procedure to insert a JTWC forecast into a NOGAPS background wind field may also provide better sea state guidance. An approach similar to this has been employed to model extreme waves using a parametric model at the Canadian Hurricane Center (MacAfee and Bowyer 2005; Bowyer and MacAfee 2005) and has yielded positive results. Finally, in a case study of Hurricane Katrina, Wang and Oey (2008) found that inserting a high-resolution analysis of the tropical cyclone (H\*WIND; Powell et al. 1998) into a GFS background yielded realistic extreme wave heights.

In the case of Yagi (2006), is it possible that the decision to sortie the navy ships from Yokosuka could have been avoided if the sea state guidance had been consistent with the JTWC forecast? Are there other benefits, such as skill, to be gained from inserting JTWC forecasts into NOGAPS background fields? The authors attempt to address these questions in this note. First, a method of inserting operational JTWC forecasts into global numerical model-generated wind fields is developed and described. WAVEWATCH III is then run with these modified NOGAPS surface winds to produce wave states that should be consistent with the JTWC tropical cyclone forecasts. Differences between the forecast sea states from NOGAPS with the JTWC forecast insertion (hereafter called JTWC/WW3) and running WAVEWATCH III with only NOGAPS surface winds (hereafter called NOGAPS/WW3) are discussed through the evaluation of two major tropical cyclone events. Due to its importance to the U.S. Navy and its sortie decisions, the Yagi (2006) case described above is evaluated. Typhoon Nargis (2008) is also discussed as an example of what can happen when there are large differences between NOGAPS and JTWC forecast tracks. Evaluations of seasonal track, intensities, and wind radii forecasts from JTWC are compared with those from NOGAPS to provide some justification for why using the JTWC forecast in WAVEWATCH III might yield better wave forecasts than using NOGAPS alone. Finally, some cautionary notes and conclusions are drawn from these specific cases and experiences from the 2008 and 2009 western North Pacific season when near-real time runs of this product were evaluated by U.S. Navy forecasters.

## 2. Methods

The philosophy chosen to develop JTWC/WW3 is to retain as much of the original JTWC analysis and

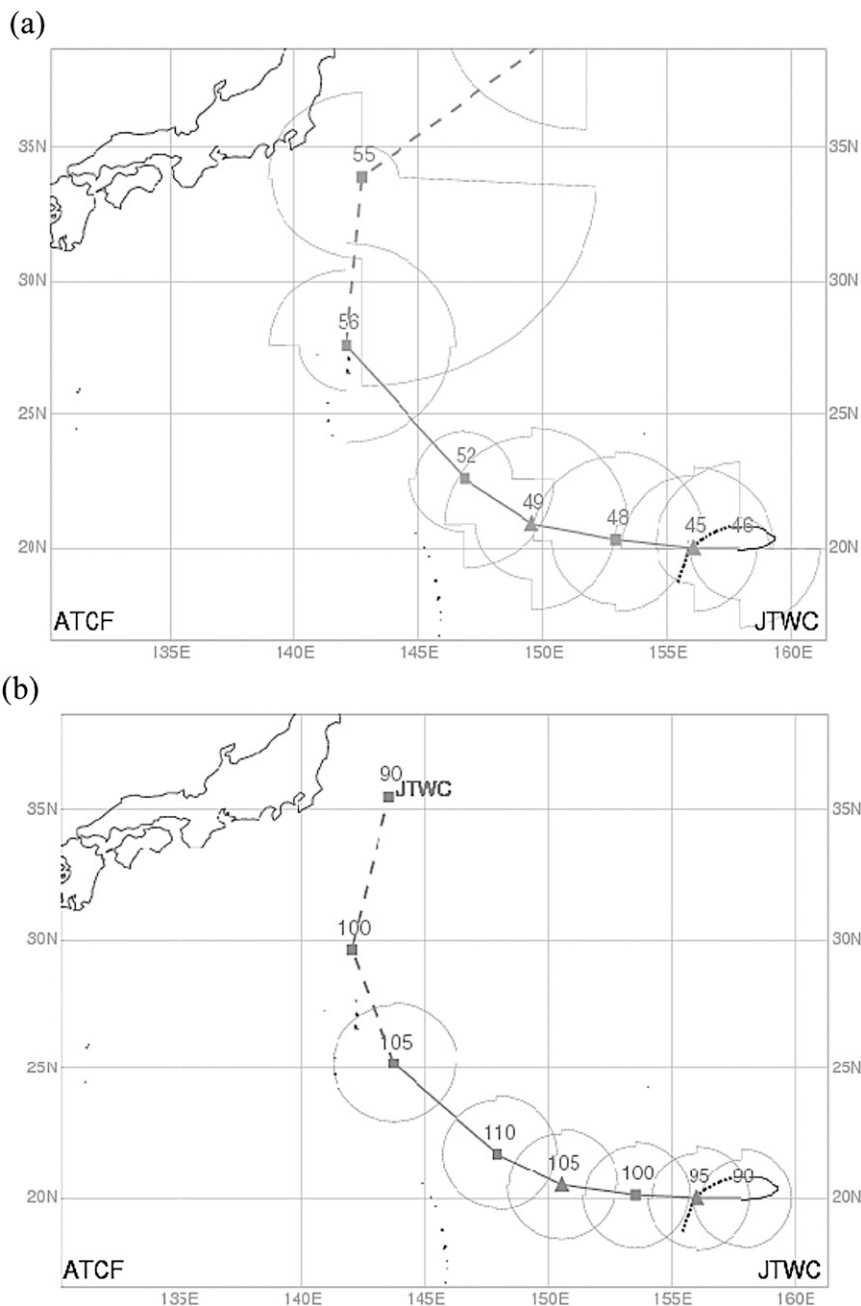


FIG. 1. The 1200 UTC 19 Sep forecasts for (a) NOGAPS and (b) JTWC during Yagi (2006). Historical track (dashed and solid curved line); 12-, 24-, 36-, 48-, 72-, 96-, and 120-h forecast positions (triangles and squares); forecast intensity [wind speed (kt)]; and forecast 34-kt wind radii are all shown. The 120-h forecast position for NOGAPS is off the map and the JTWC 34-kt wind forecasts extended only to 72 h.

forecast information as possible in the surface winds. We first remove the NOGAPS vortex from the grid and replace the removed vortex points with values generated with bilinear interpolation, which provides a complete grid without a NOGAPS vortex. We then generate a

surface vortex on a radial grid, transform the vortex to a high-resolution latitude–longitude grid, and insert the data from the high-resolution grid directly into the NOGAPS grid. These modified NOGAPS fields are then fed directly into the WAVEWATCH III model,

which is run to a forecast time that matches the last JTWC forecast time. More specific information on each of the steps is provided below.

#### *a. Vortex removal from NOGAPS surface winds*

NOGAPS 1°-resolution surface wind fields are acquired either from an FNMOC data server or from the Global Ocean Data Assimilation Experiment (GODAE) server (U.S. Navy 2008a) for the analysis period and (preferably) for 3-h intervals extending to the last time in the JTWC forecast as stored in files on the Automated Tropical Cyclone Forecasting System (ATCF; Sampson and Schrader 2000). These forecast fields are then linearly interpolated in time to produce hourly NOGAPS surface wind fields on a 0.25° latitude–longitude grid.

NOGAPS forecast positions ( $t = 0, 12, 24, \dots, 120$ ) are read from the ATCF forecast files and linearly interpolated to hourly forecast positions. The radius of the vortex removed from the NOGAPS fields is set to be the JTWC-analyzed radius of the outermost closed isobar at synoptic time (0000, 0600, 1200, or 1800 UTC). This radius is not a forecast parameter, so it remains constant throughout the entire forecast during the NOGAPS vortex removal. Bilinear interpolation is used to fill the entire space left by the vortex removal using the four closest points at the northern, southern, eastern, and western borders of the removed area.

#### *b. Vortex creation from JTWC forecast*

The parameters used to define the vortex are the intensities [maximum 1-min mean near-surface wind (kt)]; the 34-, 50-, and 64-kt wind radii; the radius of the outermost closed isobar; and the radius of maximum winds. The JTWC analysis position contains all required parameters as these are used as input into analysis applications such as the multiplatform tropical cyclone surface wind analyses (Mueller et al. 2006; Olander and Velden 2007) and to “bogus” NWP models such as NOGAPS (Goerss and Jeffries 1994) and the navy version of the GFDL model (GFDN; Rennick 1999). The JTWC forecasts can contain intensities and 34-, 50-, and 64-kt wind radii when available, but not the radius of the outermost closed isobar and not the radius of maximum winds. As a consequence, these two JTWC-analyzed parameters are assumed to be constant throughout the forecast with two exceptions provided as gross error checks. If the radius of maximum winds exceeds one of the 34-, 50-, or 64-kt forecast wind radii for a given forecast period, it is set at 5 n mi less than the highest forecast wind radius it exceeds. For each forecast, the radius of the outermost closed isobar is set to be

100 n mi greater than the largest 34-, 50-, or 64-kt wind radius.

Wind observations for all available wind radii are generated at 10° azimuth intervals for each quadrant, which results in 12 synthetic observations for each quadrant and 36 observations for the radius of maximum wind and the radius of the outermost closed isobar. An extra set of 36 synthetic observations is generated 50 n mi inside the radius of the outermost closed isobar to fill in space between the 34-kt wind radii and the outermost closed isobar. This extra set of synthetic observations was added because the authors wished to completely replace the NOGAPS circulation with one generated from a JTWC forecast, but this method could probably be refined to blend with the NOGAPS background field at a later date. Finally, all synthetic observations are converted from the 1-min mean winds that JTWC observes and forecasts into 10-min mean winds for which WAVEWATCH III has been designed. In practice, the 1-min mean winds are multiplied by a factor of 0.88 to get the 10-min mean winds, a factor used operationally at JTWC (Sampson et al. 1995) and found to be an appropriate approximation by Kruk et al. (2010). The vortex developed from the JTWC bogus for Yagi (2006) at 1200 UTC 19 September generated for a radial grid is shown in Fig. 2.

Note that the authors chose to construct a vortex directly from the official JTWC analysis and forecast rather than use a parametric model to define the vortex shape (MacAfee and Bowyer 2005) or use a parameterized model to forecast the wind structure (Knaff et al. 2007). There are some drawbacks to this in that the JTWC forecasters can easily introduce unrealistic wind radii into the vortex; however, there are advantages in that the vortex remains consistent with the JTWC forecast and therefore may have increased skill. For example, the 34- and 50-kt wind radii were shown to be skillful out to about 72 h during the 2004 and 2005 seasons (Knaff et al. 2007), so there may be some benefit to using these wind radii as input into WAVEWATCH III.

#### *c. Vortex insertion into NOGAPS surface winds*

The retrieved NOGAPS surface winds are on a latitude–longitude grid so, prior to inserting the JTWC vortex described above into this grid, the vortex is transformed into a 0.02° latitude  $\times$  0.02° longitude grid using a tessellation algorithm (O'Reilly and Guza 1993) based on the Delaunay tessellation method of Watson (1982). The tessellation routine was designed to map irregularly spaced bathymetry data to a 3"  $\times$  3" bathymetry grid for the Southern California Bight, and it attempts to retain the values of the input points, even with sharp gradients and large data voids in the original bathymetry data.

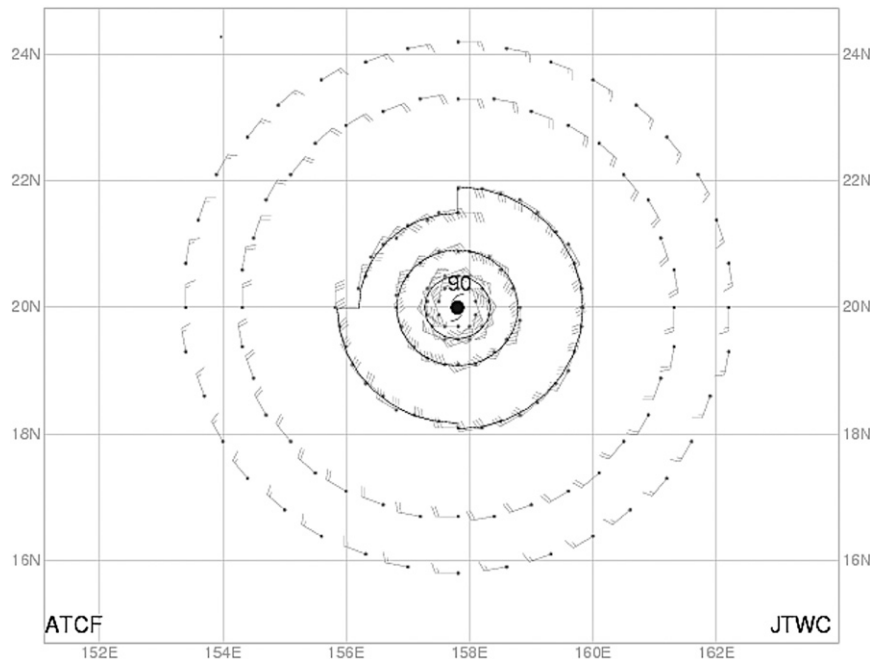


FIG. 2. Vortex generated for Yagi (2006) analysis at 1200 UTC 19 Sep. Innermost winds are at the radius of maximum winds, followed by the 64-, 50-, and 34-kt winds, and winds at the outermost closed isobar (15 kt). An extra set of winds (25 kt) is inserted 50 n mi inside the radius of the outermost closed isobar.

This is an ideal algorithm to apply to the JTWC vortex since we attempted to retain the original JTWC vortex while inserting it into the NOGAPS background. The input data for the Yagi (2006) analysis case in Fig. 2 consists of 216 input “observations” (six radii with 36 observations each) that are interpolated to a  $0.02^\circ$ -resolution grid encompassing the vortex (144 346 points).

The WAVEWATCH III domain for the western North Pacific was constructed with  $0.2^\circ$  resolution, so the NOGAPS winds are bilinearly interpolated to this grid. Finally, every 10th point from the  $0.02^\circ$  vortex grid data is obtained and substituted into the  $0.2^\circ$  NOGAPS grid to produce the final winds for WAVEWATCH III. We did not attempt to blend the vortex data and the NOGAPS data, as was done in Chao et al. (2005), but this would probably further improve the product.

#### d. WAVEWATCH III specifics

The WAVEWATCH III (version 2.23) is run on a domain for the western North Pacific that extends from  $5^\circ$  to  $45^\circ\text{N}$  and from  $100^\circ$  to  $165^\circ\text{E}$ . The model is “cold started” at the formation of the tropical cyclone, after which it is run on a 12-h update cycle for the life of the storm. The model is forced by hourly wind fields generated from the JTWC official track, as described above. Lateral boundary conditions are ignored, as the wave field is dominated by the tropical cyclone-generated waves. The drag

coefficient is limited to 0.0025, based on the findings of Donelan et al. (2004). The  $0.2^\circ$  resolution is slightly higher than that of the NAH grid ( $0.25^\circ$  resolution) used in the Atlantic. The success of this implementation, which includes vortex insertion from the GFDL model (Tolman et al. 2005; Chao et al. 2005), was a key reason for using this resolution.

### 3. Results

#### a. Yagi 2006

The NOGAPS/WW3 84-h forecast for Yagi (2006) from 1200 UTC 19 September valid 0000 UTC 23 September is shown in Fig. 3a. This 84-h NOGAPS/WW3 forecast provided guidance in making the decision to sortie the ships from Yokosuka since the 12-ft seas were forecast to impact the coast. High seas were also forecast to impact the offshore waters extending approximately 400 n mi south of Yokosuka, so approximately 24 h of travel time would be required to move south of the forecasted region of 12-ft seas. The preparedness time was factored into the decision, and the process of starting the sortie (sortie condition C—prepare to sortie within 36–48 h to avoid heavy weather) was initiated soon after reviewing this NOGAPS/WW3 run.

The JTWC/WW3 84-h forecasts for Yagi (2006) from 1200 UTC 19 September valid at 0000 UTC 23 September

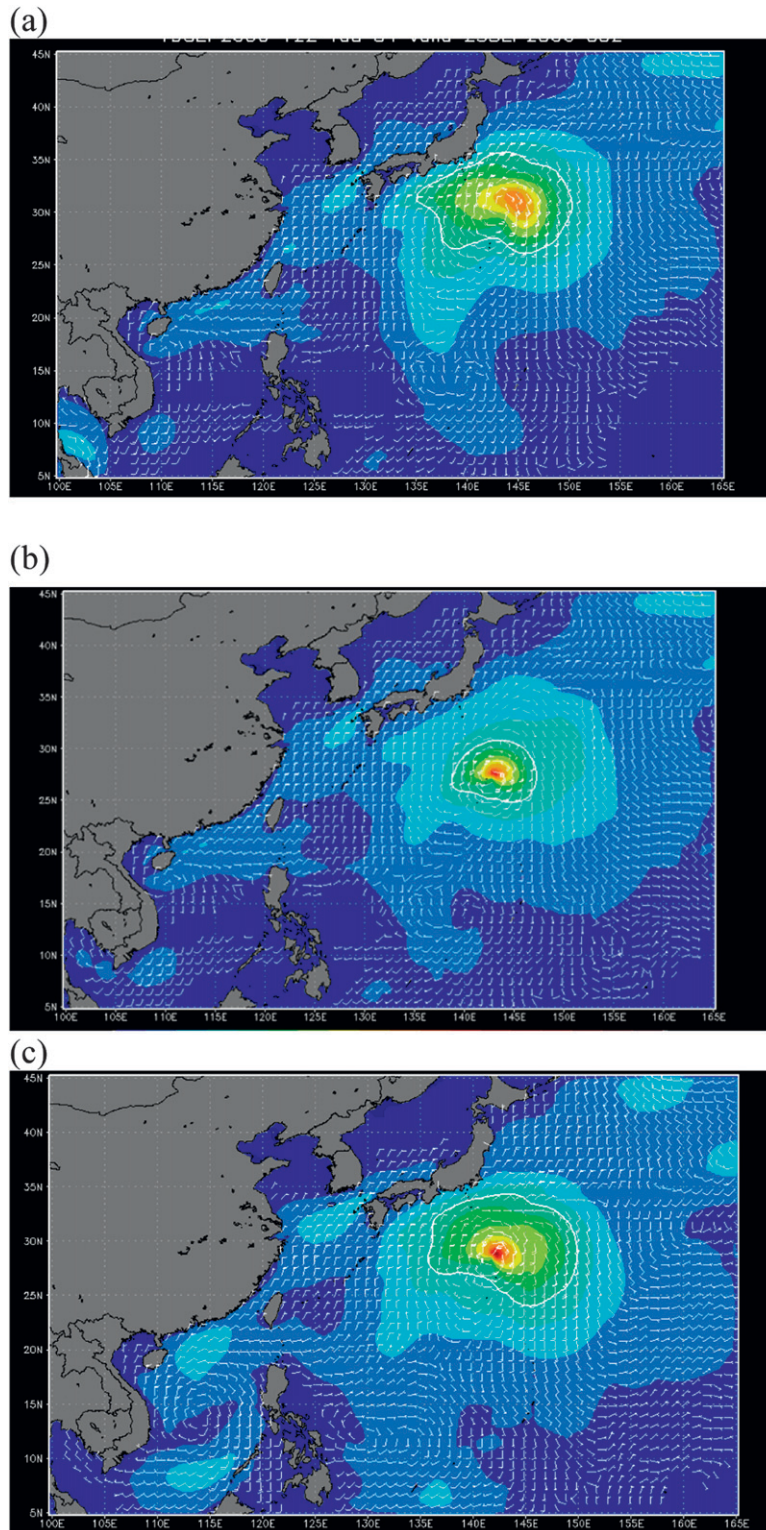


FIG. 3. (a) NOGAPS/WW3 and (b) JTWC/WW3 84-h forecasts for Yagi (2006) from 1200 UTC 19 Sep and (c) JTWC/WW3 analysis from a hindcast run valid at 0000 UTC 23 Sep. Shaded areas indicate the significant wave height (ft). Wind barbs indicate the surface winds used in WAVEWATCH III. The 12-ft seas area important for navy ship navigation is indicated as a white line.

are shown in Fig. 3b. Two major differences between this forecast and the NOGAPS/WW3 forecast are the extent and location of the 12-ft seas. The entire area of 12-ft seas is within an approximately  $8^{\circ} \times 5^{\circ}$  box located about 500 n mi off the coast of Japan. In contrast, the NOGAPS/WW3 area of 12-ft seas is within an approximately  $15^{\circ} \times 10^{\circ}$  box impacting the Japanese coast. The JTWC/WW3 108-h forecast from 1200 UTC 19 September (not shown) did have 12-ft seas grazing the coast north of Tokyo Bay, but this may not have prompted sortie preparation on 19 September since the port of Yokosuka was not forecast to receive the high winds that have impacted ships in port (Brand 2008).

In subsequent JTWC/WW3 runs from 20, 21, and 22 September, the 12-ft seas were only found to impact the coast of Japan just north of Tokyo Bay. The projected impact was found to be largest for the 60-h forecast from 1200 UTC 21 September valid 0000 UTC 24 September, where the 12-ft seas lie just off the Japanese coast outside of Tokyo Bay (Fig. 4b). The NOGAPS/WW3 forecast valid at the same time shows 12-ft seas impacting Tokyo Bay and a large area off the coast of southern Japan (Fig. 4a). A WAVEWATCH III hindcast of Yagi (2006) was also run with the JTWC bogus inserted into the NOGAPS background winds (Fig. 4c). The hindcast analysis for 0000 UTC 24 September indicates a larger area of 12-ft seas farther northeast of Yokosuka moving away from Japan. The area affected is larger than the JTWC/WW3 forecast, but smaller than the NOGAPS/WW3 forecast. The time of the nearest approach of 12-ft seas to Yokosuka in the JTWC/WW3 hindcast is at 0600 UTC 23 September when the 12-ft seas lie just east of Yokosuka and a large area south and east (not shown).

Although it is impossible to predict in hindsight sortie decisions made in real time, the JTWC/WW3 forecasts would have at least provided guidance consistent with the JTWC forecast. If forecasters had had more confidence in the JTWC/WW3 product, the sortie decision might have at least been delayed a day (from 19 to 20 September), and the distance traveled to avoid the high seas might have been reduced. Whether the sortie could have been avoided altogether is difficult to determine. The cost of staying in port and losing a ship is on the order of billions of dollars while the sortie cost is on the order of millions of dollars, so it could be argued that 100 sorties is much cheaper than losing a single aircraft carrier. The navy also combines necessary training with the sorties to use fuel and time more efficiently.

#### *b. Wave height verification for Yagi (2006)*

Two altimeter passes near the center of Yagi (2006) at about the time the 12-ft seas were nearest Yokosuka are

shown in Fig. 5. Although these altimeter passes do not give a complete picture of the wave distribution on 23 September, they do indicate that wave analyses from both algorithms appear to peak in about the right location. For this particular analysis time, the NOGAPS/WW3 appears to produce a slightly higher and more accurate wave distribution in Yagi (2006).

#### *c. Wave height verification for Nargis (2008)*

The Yagi (2006) case is one in which the NOGAPS and official JTWC forecast tracks are along a similar path. While this should occur more often as track forecasts improve, there will always be cases where the paths are quite different. Such is the case for Nargis (2008), especially between 0000 UTC 28 April and 0000 UTC 30 April. For these two days, the NOGAPS 72-h forecasts were approximately 200 n mi northeast of the JTWC forecasts, which resulted in wave fields that were separated from the tropical cyclone in the official forecast. The 1200 UTC 29 April 72-h forecast wave field from the NOGAPS/WW3 has an area of 12-ft seas north of the JTWC/WW3 and the verifying analyses (Fig. 6), but the highest seas have dissipated since the tropical cyclone made landfall near  $19^{\circ}\text{N}$ ,  $94^{\circ}\text{E}$  at 0000 UTC 29 April. The verifying significant wave height analysis for the JTWC/WW3 also appeared to be more consistent with the altimeter passes near the tropical cyclone center available on 1 May 2008 (Fig. 7).

#### *d. Track, intensity, and wind radii verification*

Bulk statistics for significant wave height would be beneficial in evaluating the performance and biases of the NOGAPS/WW3 and the JTWC/WW3; however, this has not been accomplished. One method of exploring the performance is to evaluate long-term statistics for tropical cyclone winds used as input to the NOGAPS/WW3 and JTWC/WW3 algorithms. The NOGAPS and JTWC both forecast track, intensity, and wind radii on a routine basis for all tropical cyclones in the western North Pacific. These forecasts are gathered and saved as part of routine operations at JTWC via the ATCF, and it is relatively easy to evaluate the performance of these forecasts and gather information on what tendencies to expect in the NOGAPS/WW3 and JTWC/WW3 forecasts.

A comparison of track, intensity, and wind radii forecasts for NOGAPS and JTWC for the 2006–08 western North Pacific seasons is shown in Fig. 8. The track forecast error differences (Fig. 8a) for the 3-yr dataset are small but significant at the 24-, 48-, and 72-h forecast periods. The largest track forecast differences are only about 10%, and both forecasts are significantly better than the statistical forecast skill baseline

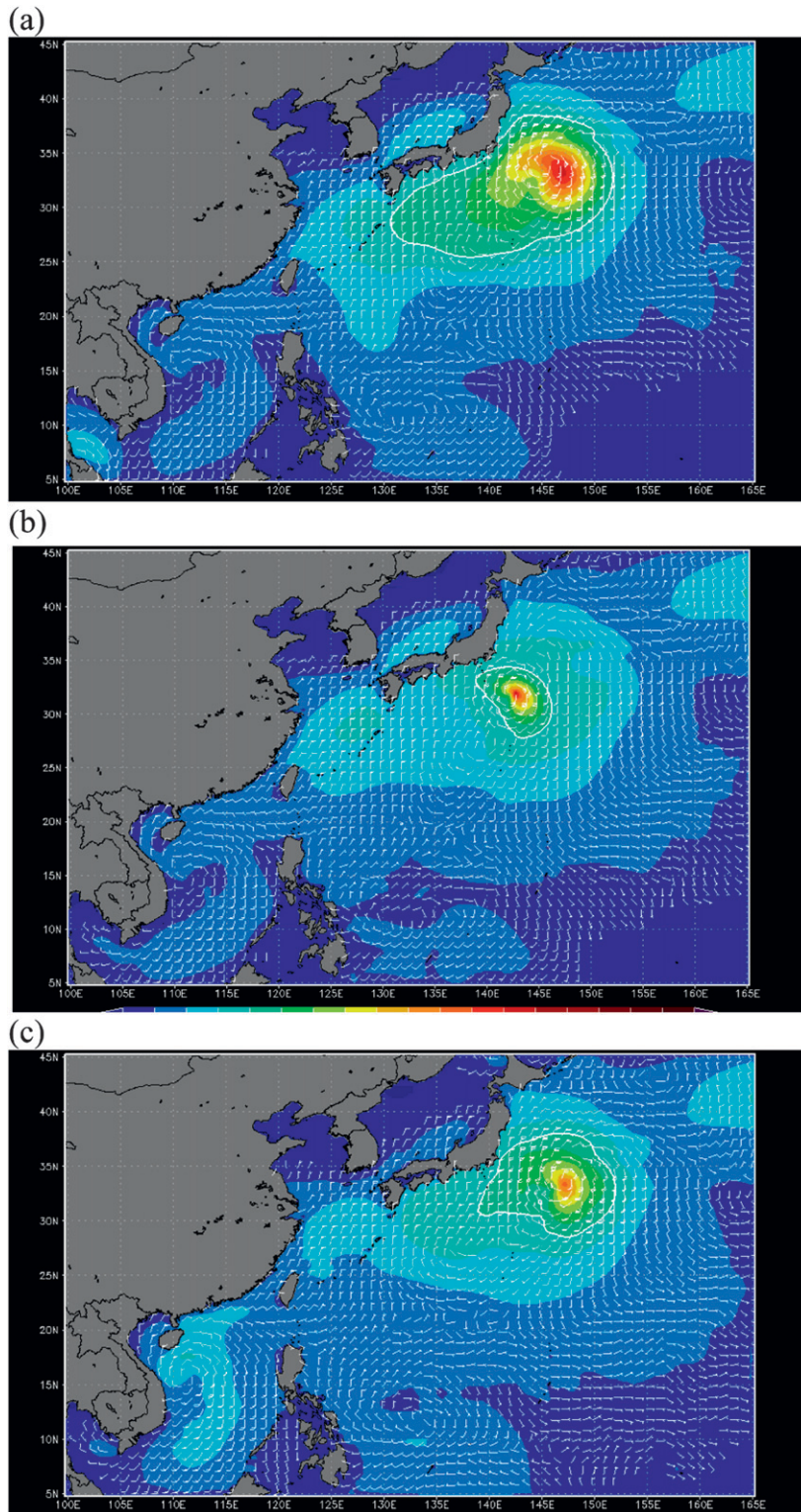
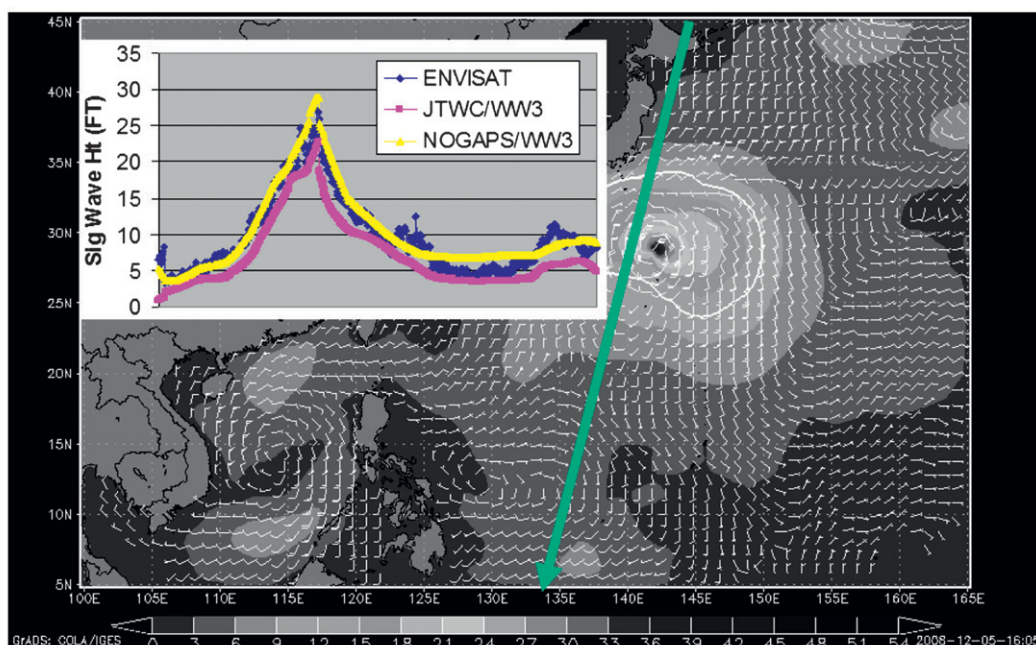
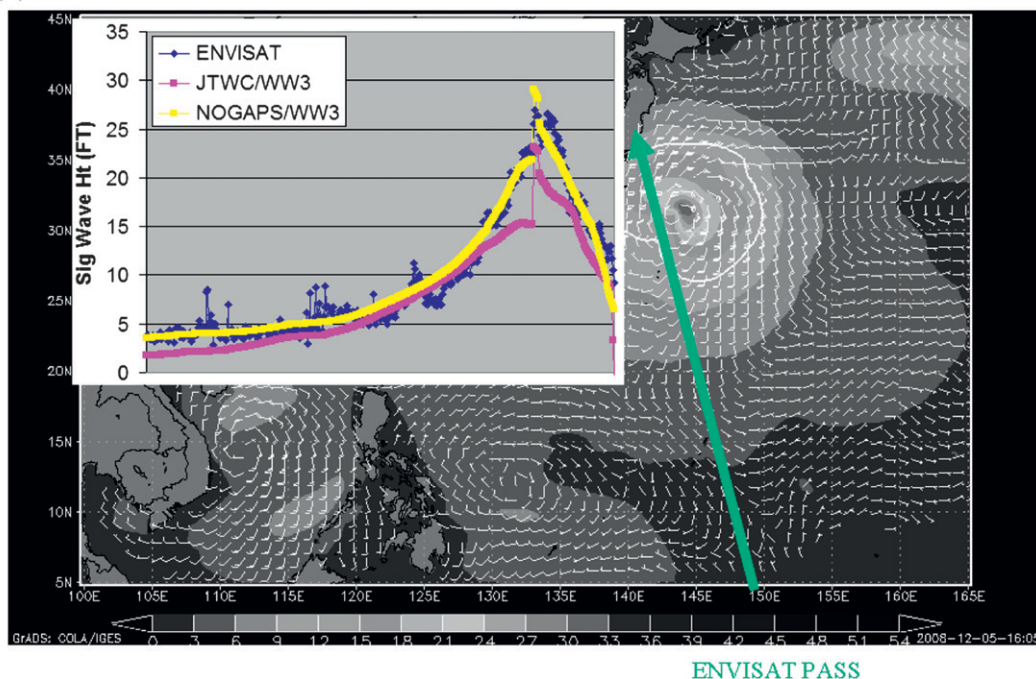


FIG. 4. (a) NOGAPS/WW3 and (b) JTWC/WW3 60-h forecasts for Yagi (2006) from 1200 UTC 21 Sep and (c) JTWC/WW3 analysis from a hindcast run valid 0000 UTC 24 Sep. Shaded areas indicate the significant wave height (ft). Wind barbs indicate the surface winds used in WAVEWATCH III. The 12-ft seas area important for navy ship navigation is indicated as a white line.

(a)



(b)



ENVISAT PASS

FIG. 5. JTWC/WW3 (purple) and NOGAPS/WW3 (yellow) hindcasts of Yagi (2006) significant wave height (m) verified against Environmental Satellite (ENVISAT) passes (blue) at (a) 0000 UTC 23 Sep and (b) 1200 UTC 23 Sep. ENVISAT passes (green) are overlaid on the JTWC/WW3 hindcast.

[the Climatology and Persistence model (CLIPER); Aberson and Sampson 2003] at all forecast times.

The intensity forecast error differences (Fig. 8b) are much larger (up to 50%), and the JTWC forecasts are

skillful relative to an intensity skill baseline (Knaff et al. 2003) out to 72 h, while the NOGAPS forecasts are unskillful at all forecast times. Differences in forecast errors are significant at all forecast times except 120 h.

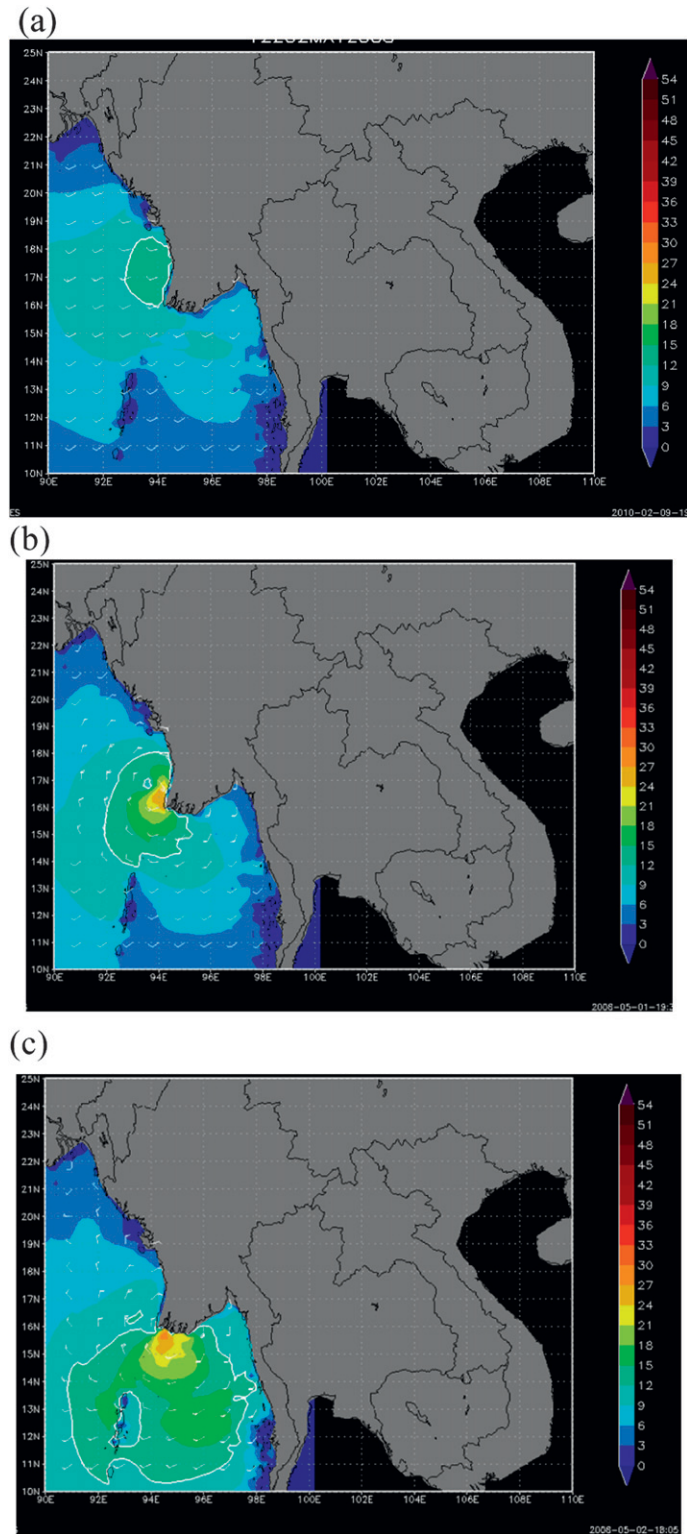
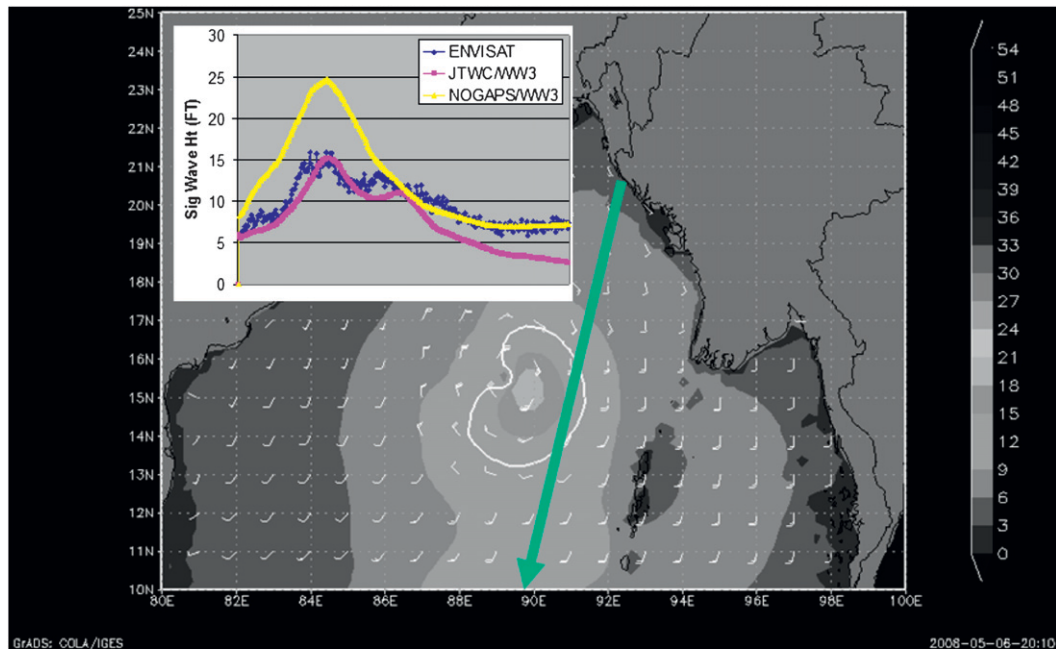


FIG. 6. The 72-h forecasts of Nargis (2008) significant wave height from (a)NOGAPS/WW3 valid at 1200 UTC 2 May, (b) JTWC/WW3 valid at 1200 UTC 2 May, and (c) the verifying JTWC/WW3 analysis at 1200 UTC 2 May. The 12-ft seas area important for navy ship navigation is indicated as a white line.



### ENVISAT PASS

FIG. 7. JTWC/WW3 (purple) and NOGAPS/WW3 (yellow) hindcasts of Nargis (2008) significant wave height (m) verified against ENVISAT (blue) at 0400 UTC 1 May. In the background, ENVISAT passes (green) are overlaid on the JTWC/WW3 hindcast valid at approximately the same time.

The intensity forecast biases (not shown) are also enlightening. While the JTWC intensity forecast biases are relatively low (0.1, 1.3, 0.9, 3.0, 6.7, and 11.8 kt at 0, 24, 48, 72, 96, and 120 h, respectively), the NOGAPS forecast intensities are large and negative (−18.5, −27.7, −31.9, −32.0, −29.1, and −24.2 kt at 0, 24, 48, 72, 96, and 120 h, respectively).

Finally, the 34-kt wind radii error differences (Fig. 8c) are also large and significant at all forecast times. JTWC does not normally forecast wind radii beyond 72 h, so the numbers of verifying 34-kt JTWC forecasts at 96 and 120 h are small. The numbers of forecasts from 0 to 72 h reflect the fact that NOGAPS fails to retain the tropical cyclone intensity and wind radii from the NOGAPS bogus (Goerss and Jeffries 1994). The bogus has also been modified (J. Goerss 2009, personal communication) so that the size of the tropical cyclone inner core is prescribed by the intensity (more intense storms have larger inner cores). This was done because it yields better NOGAPS forecast track performance. Even at the 24-h forecast period, NOGAPS retains the 34-kt winds only for 59% of the time they exist (probability of detection is 59%) while JTWC retains the 34-kt winds 93% of the time. The NOGAPS 34-kt wind radii forecasts have lower false alarm rates (18% versus 43% at 24 h), but these rates apply to only about 10% of the

total number of forecasts since NOGAPS tends to represent tropical cyclones as broad, weak circulations. The JTWC 34-kt wind radii forecasts are also skillful to 72 h compared to a statistical forecast skill baseline (a climatology and persistence forecast named DRCL; Knaff et al. 2007) while the NOGAPS 34-kt wind radii forecasts are decidedly not. The 34-kt wind radii biases (not shown) for JTWC are all under 10 n mi out to 72 h, and 20 n mi or less for the limited number of forecasts at 96 and 120 h. In contrast, the NOGAPS 34-kt wind radii biases (not shown) are between 40 and 81 n mi at all forecast lengths. For NOGAPS, the biases neither increase nor decrease substantially during the forecast. Even at analysis time, when the NOGAPS 34-kt wind radii are approximately 100 n mi, the biases represent a 50%–100% increase over the JTWC-analyzed wind radii.

In summary, statistics for the wind input to NOGAPS/WW3 and JTWC/WW3 indicate that the tracks, intensities, and wind radii for JTWC/WW3 are more skillful than the input to NOGAPS/WW3. The NOGAPS tropical cyclones tends to be weaker and larger than the JTWC tropical cyclones, so it is suspected that on average the NOGAPS/WW3 areas of high significant wave heights near tropical cyclones would be larger with lower maximum sea height than those generated by JTWC/WW3.

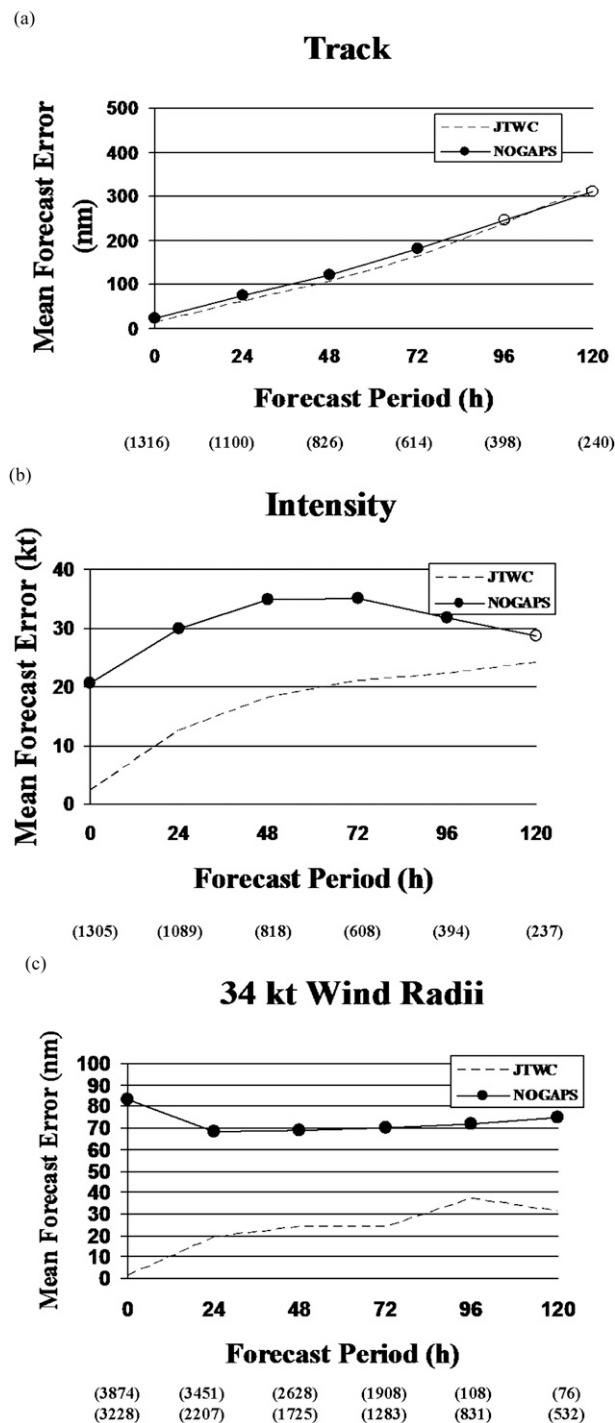


FIG. 8. NOGAPS and JTWC mean forecast errors (2006–08 western North Pacific seasons) for (a) track (n mi), (b) intensity (kt), and (c) wind radii (n mi) for each forecast period (h) listed along the  $x$  axis. Statistically significant differences in the mean forecast errors are indicated by solid circles along the NOGAPS forecast error trend. Numbers of cases are included in parentheses at the bottom of each forecast period. Top (JTWC) and bottom (NOGAPS) numbers of cases in (c) differ because not all forecasts contain 34-kt wind radii.

## 4. Summary and conclusions

A new algorithm to generate wave heights consistent with tropical cyclone forecasts from JTWC (JTWC/WW3) has been developed. The process involves generating observations from the forecast track and 34-, 50-, and 64-kt wind radii. The JTWC estimate of the radius of maximum winds is used in the algorithm to generate synthetic observations for the forecast intensity (wind), and the JTWC-estimated radius of the outermost closed isobar is used to assign observations at the outermost extent of the tropical cyclone circulation. These observations are then interpolated onto a  $0.2^\circ$  latitude–longitude grid covering the entire extent of the circulation. Finally, NOGAPS model fields are obtained for each forecast time, the NOGAPS model forecast tropical cyclone is removed from these fields, and the new JTWC vortex is inserted. These modified fields are then used as input to WAVEWATCH III to generate wave forecasts that are consistent with the JTWC forecasts.

The JTWC/WW3 algorithm is applied to Typhoon Yagi (2006), in anticipation of which U.S. Navy ships were moved from Yokosuka, Japan, to an area off the southeast coast of Kyushu. The decision to move (sortie) the ships was based on NWP model-driven long-range wave forecasts, which indicated a large area of high seas impacting the coast in the vicinity of Tokyo Bay. The sortie decision was made approximately 84 h in advance of the high seas in order to give ships time to steam the approximately 500 n mi to safety. Results for the new algorithm indicate that the high seas would not affect the coast near Yokosuka. Although this specific forecast verifies, the JTWC/WW3 algorithm does not outperform the NWP model-driven wave analysis and forecasts for Yagi (2006).

Typhoon Nargis (2008) is used to illustrate what can happen when NOGAPS and JTWC track forecasts diverge. In this particular case, JTWC track forecasts outperformed the NOGAPS forecast, so the resulting NOGAPS forecasts of highest significant wave heights were in an area of relatively calm seas. It is important to note that the reverse can also happen.

The JTWC track, intensity, and wind radius forecasts are shown to generally outperform those of NOGAPS. The largest discrepancies are between the forecast intensities and the 34-, 50-, and 64-kt wind radii; the JTWC forecasts of these are significantly superior to those of NOGAPS. This result is expected since NOGAPS does not have the resolution or physics to resolve tropical cyclones. The NOGAPS/WW3 analysis and forecasts of significant wave heights near Yagi (2006) were surprisingly good. Although the NOGAPS intensity forecasts were too low throughout the storm, the 34-kt wind radii

were too large. These biases apparently compensate for each other in WAVEWATCH III, so that the result is a useful significant wave height field. However, in cases where the NOGAPS track is far from the verifying track, the NOGAPS/WW3 forecasts of tropical cyclone-generated seas will be geographically misplaced. Such was the case with Nargis (2008).

The JTWC/WW3 has been running in near-real time for approximately 2 yr. Forecasters at the U.S. Naval Maritime Forecast Center (NMFC) and others have been evaluating the significant wave height and other products online ([http://www.nrlmry.navy.mil/atcf\\_web/wavewatch/page/web/tcww3.php](http://www.nrlmry.navy.mil/atcf_web/wavewatch/page/web/tcww3.php)).

Comments and anecdotal evaluations from the 2008 and 2009 seasons have been mostly positive, and the authors attribute the acceptance as a general desire by forecasters to have consistent tropical cyclone warning products. One impression from both forecasters and developers is that NOGAPS/WW3 generally forecasts larger regions of 12-ft seas than does JTWC/WW3. This seems logical since the NOGAPS tropical cyclone circulation tends to have a positive bias in 34-kt wind radii relative to the JTWC forecasts (Fig. 8). At the same time, it is also likely that the JTWC/WW3 maximum wave heights are higher near the center of tropical cyclones since the intensities are generally higher than those in NOGAPS. A more exhaustive evaluation is needed to validate whether these suspicions are true.

The NOGAPS/WW3 model was upgraded on 16 September 2009 to include observations in its analysis so that the analysis should compare favorably with the altimeter observations (Cummings and Wittmann 2009). The upgrade uses the Navy Coupled Ocean Data Assimilation technique (NCODA; Cummings 2005) to assimilate significant wave height observations from altimeters. The data assimilation reduces both the (low) bias and the root-mean-square error of the analyses and shorter-range forecasts. The improvement in the analysis was apparent during Typhoon Parma, which occurred during 2009 in the western North Pacific. The NCODA analysis and JTWC/WW3 also appear to be well correlated for the cases inspected.

One final warning on the use of a product such as JTWC/WW3 is that the quality of the product is dependent on the quality of the operational forecast. As seen in Fig. 8, the mean JTWC forecasts of track, intensity, and wind radius are generally more accurate than those from NOGAPS; however, individual cases can vary widely. Applying the JTWC/WW3 12-ft seas without caveats of the forecast uncertainty could introduce problems for navy customers. One solution to this is to develop an uncertainty product based on JTWC/WW3. The authors intend to investigate the

feasibility of developing such a product in the near future.

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